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EMPIRICAL MODEL OF VERTICAL GROUND MOTIONS FOR ENGINEERING DESIGN

ABSTRACT

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The current engineering approach to simulating site-specific vertical ground motions starts with rock-outcrop horizontal motions, converts them into the vertical component using an empirical *V/H* ratio for response spectra, and propagates the resulting motion through the soil column as a vertically incident *P*-wave. In the absence of data on strain-dependent soil properties in compressional deformation, strain-compatible shear-wave properties from the horizontal-component analyses are utilized. This approach makes two assumptions: (1) that the vertical motions are primarily composed of compressional waves and (2) that strain-dependent material properties in shear deformation can be extrapolated to compressional deformation. Our study deals with the empirical validation of both assumptions. First, we investigated the ratio of *SV*- to *P*-wave spectra of the vertical component of ground motions from significant recent events in California to find which wave type predominantly contributed to vertical motions, in the frequency range of 0.5 to 12.5 Hz. The results indicate that shear waves dominate the vertical motions at frequencies up to approximately 10 Hz, above which the contribution of compressional deformation is about as strong or greater. This result holds for both soil and rock sites. Second, using the data from the KiK-net borehole arrays in Japan, we estimated the nonlinearity in compressional deformation by studying *P*-wave amplification at variable amplitude levels. Frequency shifts and in some instances reduced amplification, compatible with the hysteretic softening type of nonlinearity known for shear waves, is found as the amplitude of compressional strain increases. A tentative curve of constrained-modulus reduction is also similar to the existing shear-modulus reduction curves.

The results of this study suggest that for most practical applications, vertical motions can be modeled as non-vertically propagating *SV*-waves. This could be implemented through conventional one-dimensional horizontal-component modeling using SHAKE and the application of empirical depth-dependent *V/H* correction factors to account for an inclined propagation path. At high frequencies, vertical motions may have to be modeled as near-vertically propagating *P*-waves, with strain-dependent properties

specifically developed for compressional deformation; however, these frequencies may be of lesser importance for design applications.